AD-A149 074 FUNDAMENTAL STUDIES ON MPD THRUSTERS(U) CARNEGIE-MELLON UNIV PITTSBURGH PA DEPT OF MECHANICAL ENGINEERING J L LAWLESS 1983 AFOSR-TR-84-1194 AFOSR-83-0033 1/1

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Fundamental Studies on MPD Thrusters

Annual Technical Report

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(412)-578-3641

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 84-1194
6a. NAME OF PERFORMING ORGANIZATION Carnegie Mellon University 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR/NA
6c. ADDRESS (City, State and ZIP Code) Department of Mechanical Engineering Pittsburgh, PA. 15213	7b. ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB, DC 20332
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFOSR 8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-83-0033
8c. ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB, DC 20332	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 61102F PROJECT NO.: 61102F TASK NO.: 2308/K1 WORK UNIT NO.:
11. TITLE (Include Security Classification) FUNDAMENTAL STUDIES ON MPD THRUSTERS	
12. PERSONAL AUTHOR(S) John L. Lawless	
13a. TYPE OF REPORT ANNUAL 13b. TIME COVERED FROM ______ TO ______	14. DATE OF REPORT (Yr., Mo., Day) 1983 15. PAGE COUNT
16. SUPPLEMENTARY NOTATION	
17. COSATI CODES FIELD / GROUP / SUB. GR.	18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report summarizes progress made during the first year of the grant to study MPD thrusters. The major goals of this work are to determine erosion rates and the limits of diffuse mode operation. Major accomplishments of the first year include:

a. identification of a nondimensional flow scaling parameter

b. identification of a new mode of "onset"

c. a proposal for an improved design

d. prediction of an anode thermal instability

These and other accomplishments are described in section 3 of the report.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Leonard Caveny	22b. TELEPHONE NUMBER (Include Area Code) (202) 767-4937 22c. OFFICE SYMBOL NA

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

SECURITY CLASSIFICATION OF THIS PAGE

Table of Contents

Annual Technical Report

Fundamental Studies on MPD Thrusters

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1. Introduction

This report summarizes progress made during the first year of this grant to study MPD thrusters. The major goals of this work are to determine erosion rates and the limits of diffuse mode operation. Major accomplishments of the first year include:

- identification of a new mode of "onset",
- identification of a nondimensional flow scaling parameter,
- a proposal for an improved design, and
- prediction of an anode thermal instability.

These and other accomplishments are described in section 3.

2. Research Objectives

Reliability is a major concern in any space engineering problem, and the reliability of MPD thrusters is limited by erosion. Not only are the erosion rates of MPD thrusters poorly known, the erosion mechanisms are also uncertain. Spots, evaporation, and various mechanisms for sputtering are possible. The objectives of this research are to determine when low erosion rates are possible and to quantify them.

Major differences in erosion mechanisms are expected between quasi-steady and steady operation. In quasi-steady operation, the electrodes remain cold except at local hot spots on the cathode through which the current is conducted. In steady operation, the electrodes become warm and current may be conducted diffusely. As opposed to steady operation, quasi-steady operation (1) allows smaller power supplies to be used, but, however, (2) requires large power conditioning equipment, and (3) is expected to have erosion rates over a hundred times than in diffuse mode. This work concentrates on the finding erosion rates in the diffuse mode and the limits of diffuse mode operation. This work and that of Dr. Shrade are thus complementary since he is investigating spot erosion rates for MPD thrusters.

In the diffuse-mode, evaporation and sputtering are possible erosion mechanisms. Sputtering rates are determined by how and where high-energy ions are created and how they travel to the walls. Kuriki and Onishi[1] hypothesized that high energy ions are created in the anode sheath and subsequent acceleration through the plasma to reach the cathode. This mechanism requires (1) the plasma density at the anode must be low enough that at positive sheath drop occurs, and (2) the plasma density in the bulk must be low enough that the high speed ion may pass through it without collision.

Alternatives to the Kuriki-Onishi[1] mechanism involve thermal processes. Ions from the high-energy tail of a Maxwellian distribution, for example, may cause sputtering. Also, if the plasma, which is at temperatures over 10,000K, heats the electrode surface, then evaporation may be be important. Both of these processes depend strongly on the plasma sheath structure, the plasma temperatures and densities just outside the sheath. Consequently, both of these depend on the nature of the supersonic boundary layer and its recovery temperature.

In all the erosion processes, multi-level ionization/recombination kinetics play an important role. This is because (1) sheath structure is determined in part by the ionization fraction at the wall, (2) sputtering rates would be greatly altered if doubly charged ions were present, (3) inelastic collisions play a major role in determining the electron temperature, and (4) radiation from excited levels may change the electrode heat balance.

As seen at the beginning of the reporting period, the following were considered important:

- Develop and extend a simple flow model.
- Analyze non-equilibrium effects
- Quantify the Kuriki-Onishi[1] erosion mechanism.
- Analyze the stability of the diffuse mode discharge.

As the work progressed, the flow model development lead to new and unexpected results concerning onset and erosion. These results indicated that other erosion mechanisms may be more important than that proposed by Kuriki and Onishi[1]. The reasons for this are discussed in subsection 3.1. It now seems that the thermal erosion processes are more important. This lead to new goals:

- Quantify the the thermal boundary layer behavior.
- Analyze the cathode sheath.
- Estimate sputtering rate.
- Estimate evaporation rate.

3. Status of the Research Effort

3.1. Analytical Flow Modeling

(J. Lawless, and V. Subramanian)

The analytical flow modeling effort effort has yielded a major new result: the prediction of a new mode of onset. This has important implications for the nature of erosion near onset. The model has identified a scaling parameter which characterizes the flow. This parameter is S^*, the magnetic force number evaluated at the choking point. It has also suggested possible design improvements which may lead to more efficient thrusters.

This modeling effort attempts to discover basic physics of MPD flows. Consequently, some simplifying assumptions are necessary. The model assumes one-dimensional channel flow neglecting friction and is based on the approach of King et. al.[2]. The numerical work described in later sections will be used to confirm and refine these predictions.

Previous theories had assumed that onset was associated with a change in sign of the anode sheath voltage drop. Kuriki and Onishi[1] pointed out that this change in sign may lead to the production of high energy ions and hence cause erosion by sputtering. In the new model, onset is caused by a large back-EMF blocking the current flow. Experimental evidence as to which mode of onset occurs first under which conditions does not yet exist.

The new theory of onset lead to a proposed design change to overcome the back-EMF problem. In the new design, segmented electrodes are used to vary the electric field along the channel. The electric field is increased in the middle where the back EMF is largest. The segmented electrodes may also be used to decrease the electric field near the exit if the anode sheath limit is important.

The results of this work indicate that the Kuriki-Onishi[1] mechanism may not be dominant. The reasons for this are:

- The anode limit will not be important if the back-EMF limit is reached first.
- Even if the anode sheath limit occurs first, the Kuriki-Onishi[1] erosion mechanism may be suppressed by:
    - Operating not so near onset.
    - Using segmented electrodes.
    - Injecting mass through the anode to increase the density there.

3.2. Stability of the Diffuse Discharge

(J. Lawless, and V. Subramanian)

An analysis of the heat transfer across the anode sheath has lead to an important result: the anode may be thermally unstable if a critical current density is exceeded. The analysis was performed assuming that the MPD thruster was operated continuously, as opposed to quasi-steady, and that the anode was cooled by black-body radiation.

3.3. Numerical Flow Modeling: Steady

(J. Lawless, and D. Cox)

To extend the analytical work, a computer model is being developed to solve the quasi-one-dimensional steady MPD flow including non-ideal gas effects such as varying specific heats, ionization kinetics, and channel area variation. This work is important for obtaining more quantitative estimates of flow temperatures and densities. At the close of the reporting period, this program was in the process of being tested and debugged.

3.4. Numerical Flow Modeling: Unsteady

(J. Lawless, and E. Richley)

A much more sophisticated and also computationally-demanding program is also under development. This program models *unsteady* quasi-one-dimensional plasmadynamic flow including separate electron and heavy particle temperatures,, and chemical nonequilibrium. Species diffusion velocities are found by simultaneous solution of the species momentum equations rather than the simple and, in this case, inaccurate Fick's law.

A major feature of this program is that it is user-friendly and quite flexible. It is very easy to change the species included in the model and add new reactions to the kinetics. Such changes are made using a simple control language. This is done using an operating system, THOR, specially developed for the purpose.

Because of its user-friendly and flexible nature, we expect other researchers in this field to find the program useful. When development is completed, we will distribute it.

3.5. Multi-Level Calculation of Ionization/Recombination Kinetics

(J. Lawless, D. Konopka, and V. Subramanian)

A computer program has been constructed to determine the ionization/recombination rates in atomic plasmas, which we will need for determining such rates in gases of concern for MPD

thrusters. The program considers both single step and multistep processes and includes both electron-atom collisions and radiative transitions. It can handle a large number of atomic levels -- thirty or more may be used in a typical calculation. For each pair of levels collisional and radiative rate constants may be specified. The computer program outputs the net ionization rate constants, the recombination rate constants, and the populations of the excited levels. The program algorithm follows the formulation of Bates, Kingston, and McWhirter[3].

Activities underway and/or planned for the next year to enhance the computer program involve the following modifications:

- Inclusion of atom-atom collisional processes.
- Calculation of the contribution of electronic excitation levels to the plasma internal energy and specific heat.
- Modeling of multiply ionized species.
- Calculation of the plasma energy loss rates by radiative emission from excited levels. (This is needed in the plasma energy balance equation; it also allows the interpretation of experimental spectroscopic data for better plasma diagnostics).

3.6. Inelastic Collisional Rate Constants

(D. Konopka and J. Lawless)

The calculation of the ionization/recombination kinetics discussed in the previous section requires as input values for inelastic electron-atom collision cross-sections. While some experimental values are available, many more are needed. Much theoretical work has been done in the last twenty years directed at estimating such cross-sections. We have applied two of these theories in estimating cross-sections needed for our research. The theory of Mansbach and Keck[4], which resulted from classical Monte-Carlo trajectory calculations of electron-atom collisions, applies to thermal electrons whose temperature is much lower than an ionization potential. Over its range of validity, the predictions of this theory have been found to agree well with experiment. The Bethe-Born approximation[5] is one of the oldest quantum-mechanical theories to estimate inelastic electron-atom collision cross-sections. It is valid at very high electron impact energies and, therefore, complements the theory of Mansbach and Keck. Future work will look into other theories for estimating electron-atom collision cross-sections which bridge the gap between the two theories already implemented.

3.7. Radiative Rate Constants

(V. Subramanian and J. Lawless)

A major uncertainty in the modeling of MPD thrusters is how the cold gas initially ionizes when it enters the flow channel. Two possibilities are radiative heat transfer and photo-ionization. This can be modeled if radiative rate constants for the important transitions can be found. Rate constants are needed for both bound-bound and bound-free transitions. Experimental values for these rates exist for a large number of transitions. Furthermore, some sophisticated quantum-mechanical calculations for these rates exist in the literature. We have incorporated such available values into our computer program. We have utilized a quantum mechanical theory, based on the quantum defect theory of Burgess and Seaton[6] as modified by Dy and coworkers[7,8], to estimate values of rates that were not available in the literature.

4. Personnel

- John L. Lawless: Principal Investigator
- Edward Richley: Graduate Student
- Brian Sauk: Graduate Student
- Viswanath Subramanian: Graduate Student
- Daniel Cox: Undergraduate Student

5. Interactions

Spoken papers were delivered at:

- NASA MPD Thruster Review Meeting at JPL, May 26, 1983.
- MPD Review Meeting at R & D Associates, September 27, 1983.
- AFOSR/AFRPL Contractors Review Meeting at Lancaster, March 14,1984.

In addition to the above meetings, informal discussions were held (1) with M. Martinez-Sanchez in Boston during September, 1983, and (2) with F. Mead and R. J. Cassady at AFRPL in March, 1984.

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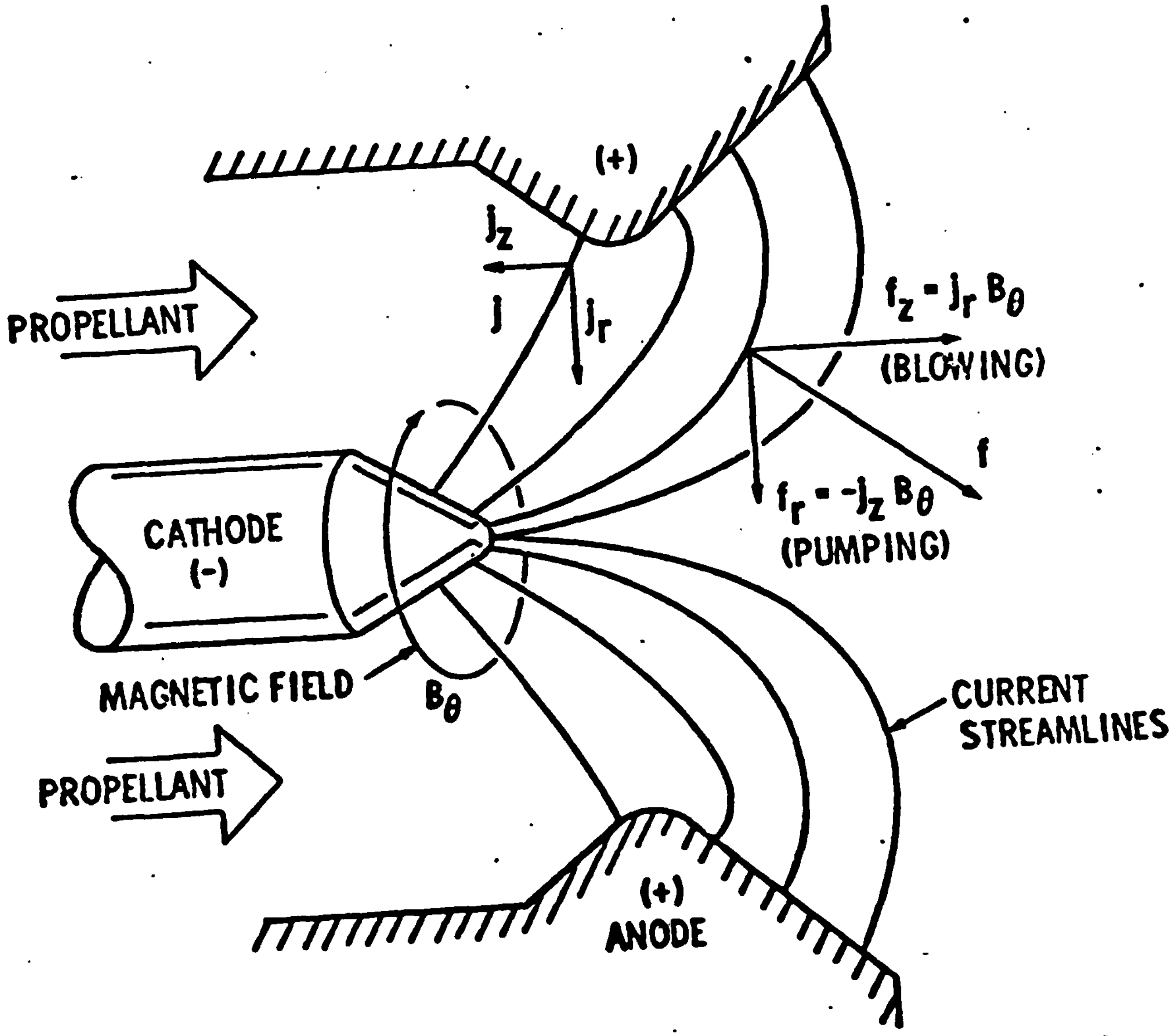

FIG. 1: A typical configuration for a MPD Thruster

This shows how a transverse magnetic field can interact with current to accelerate the flow in a self-field MPD thruster.

Analytical Flow Modeling

Technical Approach

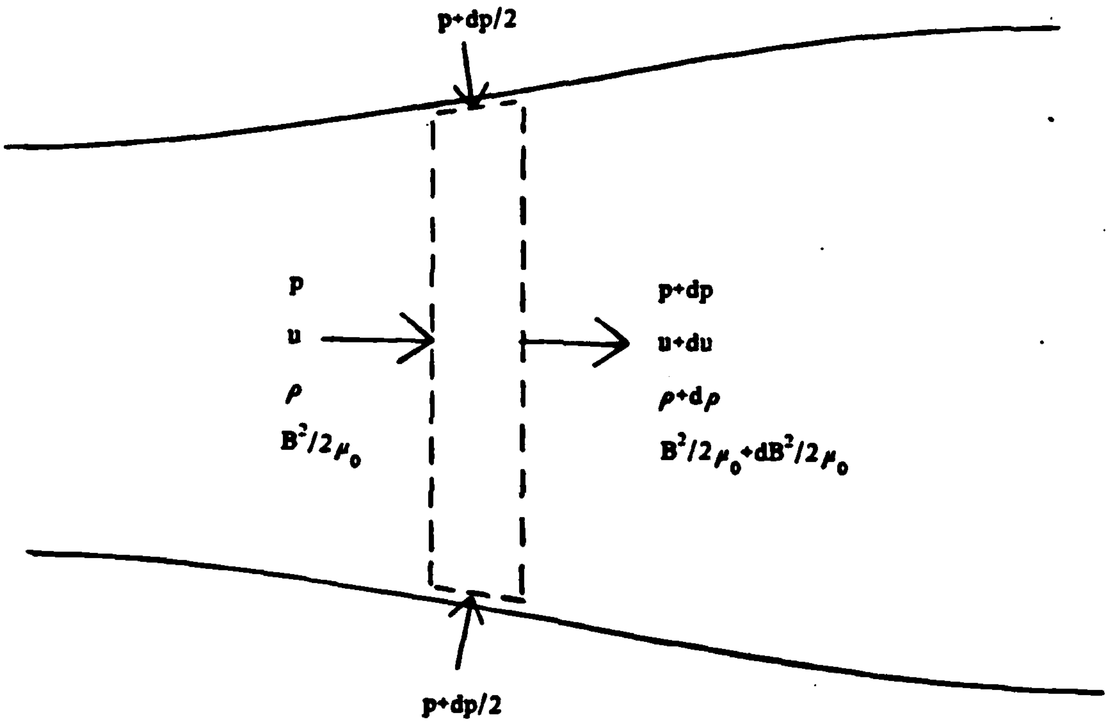

FIG. 2: The quasi-one-dimensional flow model approach is shown

Despite the simplicity of the quasi-one-dimensional approach, its implications for MPD thrusters have not yet been fully explored:

- The limits that Back-EMF places on current flow are not fully understood
- The limits that the anode sheath places on current flow are not fully understood
- The effects of area change are not known
- The effects of changing propellant species are not understood

Analytical Flow Modeling

Expected Results

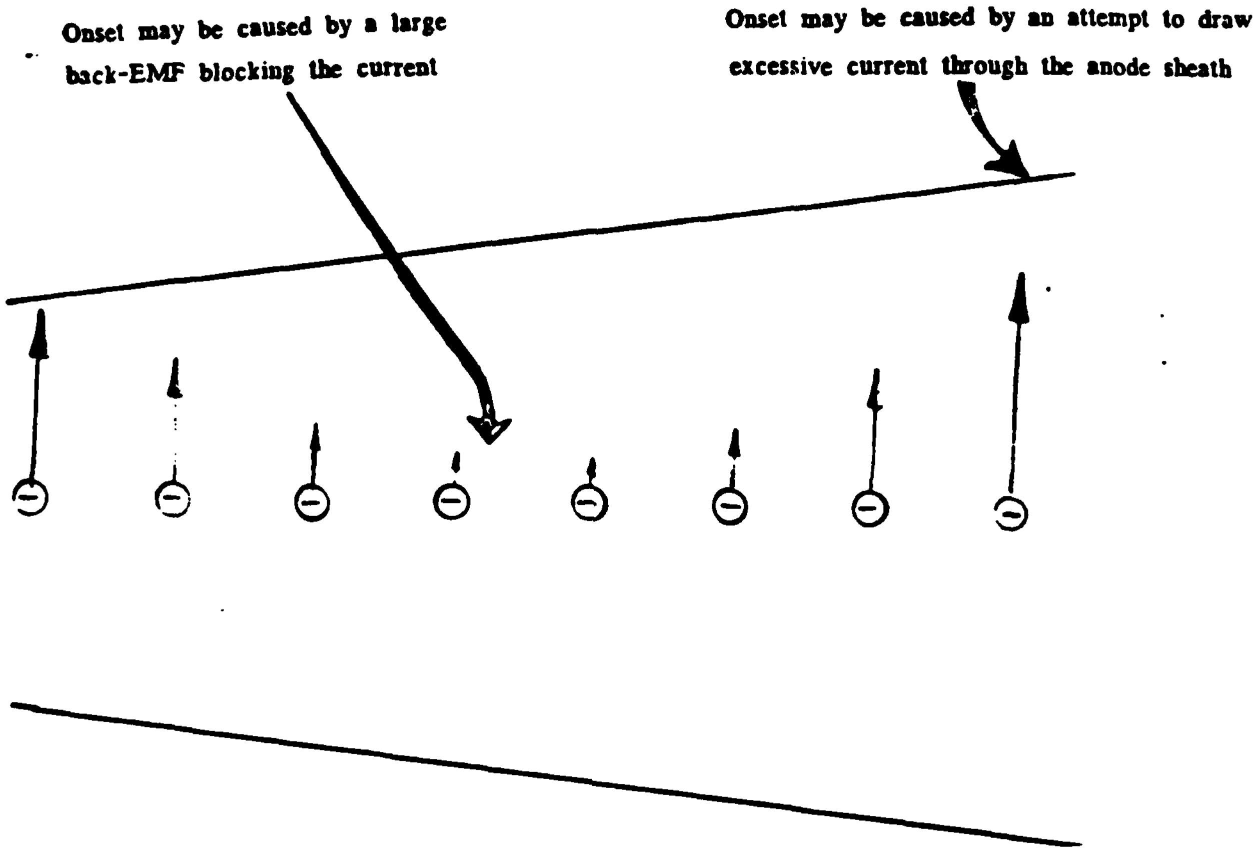

FIG. 3: The back-EMF mechanism for onset is illustrated

Ionization/Recombination Kinetics:

Technical Approach

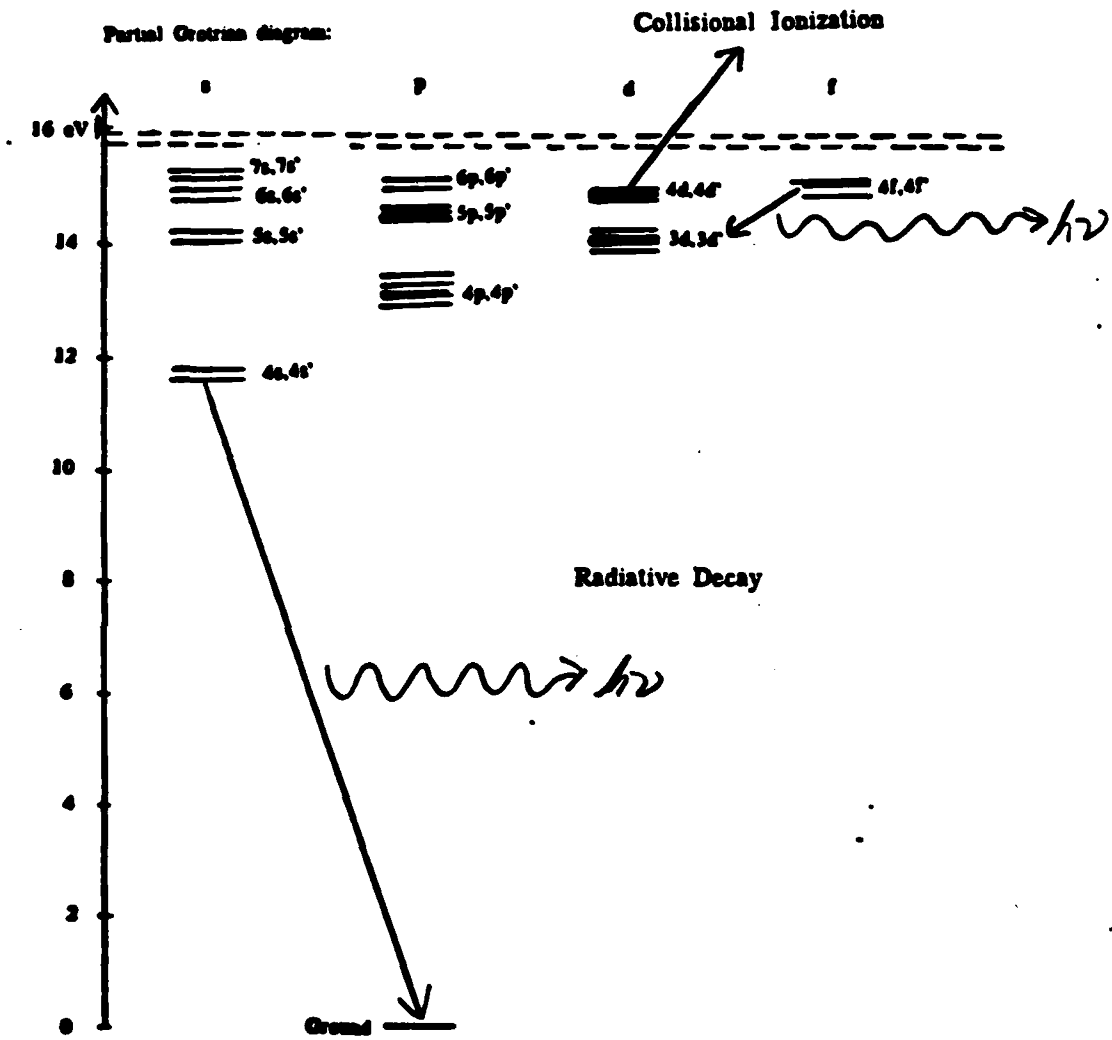

FIG. 4: An atomic energy level diagram showing the issues involved in ionization/recombination kinetics

For argon under MPD operating conditions,

- It is not known how seriously radiative emission slows ionization rates.
- It is not known how strongly radiative emission enhances recombination rates.
- It is not known whether the incoming cold gas is initially ionized by radiative or collisional processes.

Ionization/Recombination Kinetics:

Expected Results

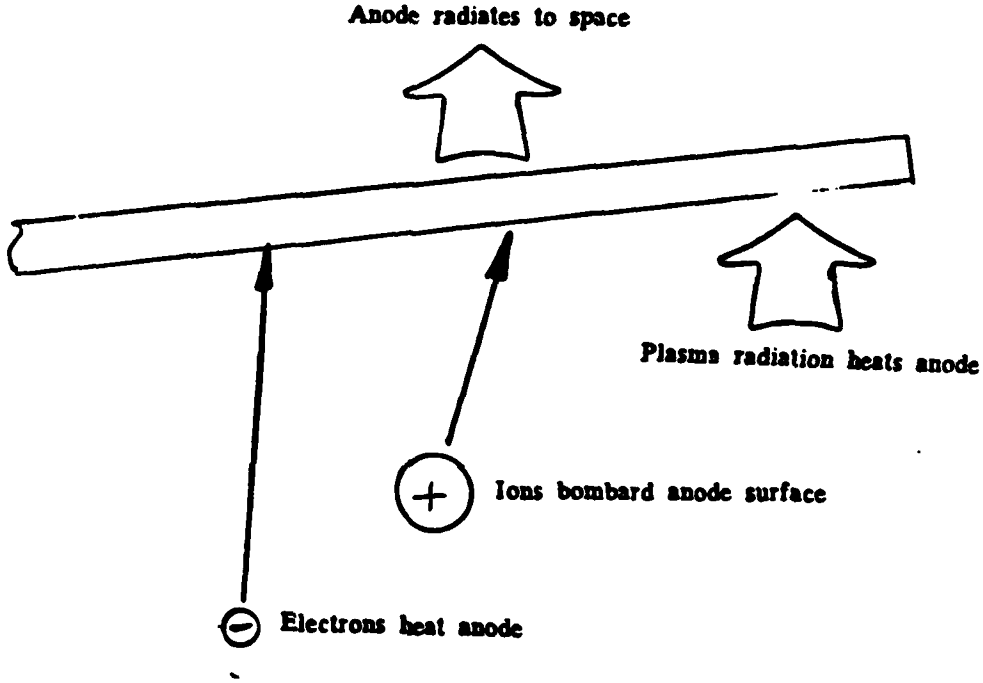

FIG. 5: Radiation is an unknown factor in the anode heat balance

- **In steady-state operation, anode cooling must balance anode heating.**
- **This heat balance places important limits on the power density of MPD thrusters**
- **An expected result of this work is to determine the importance of plasma radiation compared to electron and ion heating.**

Ionization/Recombination Kinetics:

Expected Results

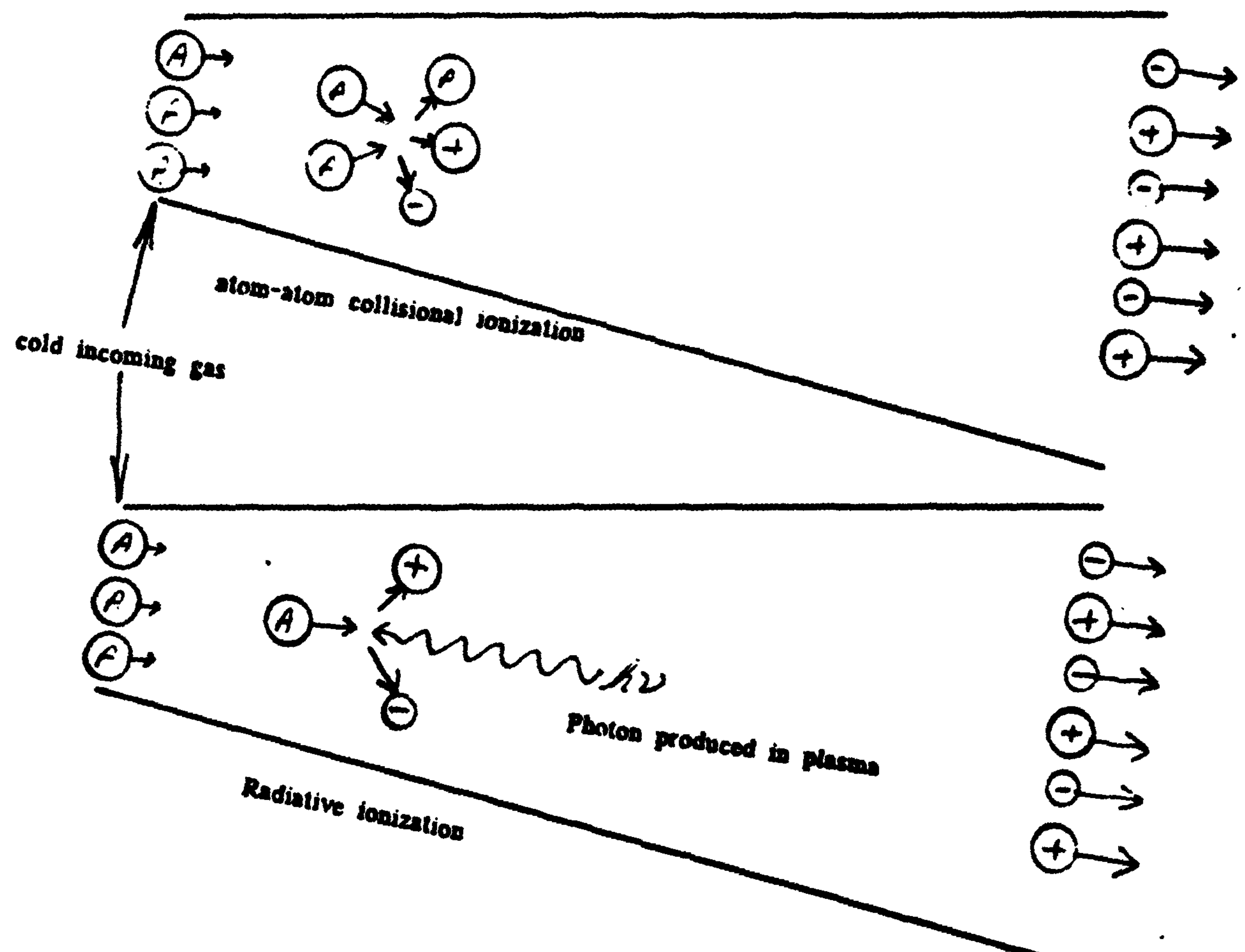

FIG. 6: The mechanism of initial ionization of the cold incoming gas is unknown and possibly important

For stable operation, the cold incoming gas must be, by some mechanism, ionized. Otherwise extinction results, as has been observed experimentally.

This work will resolve the relative importance of the following mechanisms:

- atom-atom collisional ionization
- electron-atom collisional ionization
- radiative ionization
- *A multi-step combination of the above*

Ionization/Recombination Kinetics:

Expected Results

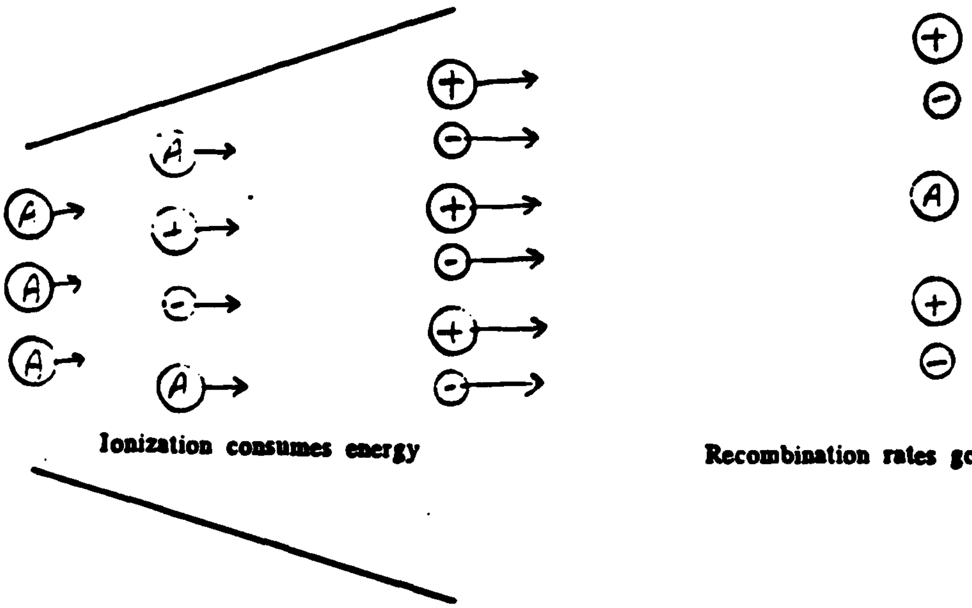

FIG. 7: Ionization and recombination rates affect thruster efficiency

Depending on ionization rates, thermal energy may go into:

- translational energy, leading to greater pressure and thrust
- Ionization energy, leading to higher frozen flow losses

Depending on recombination rates, the heat of formation of ions in the exhaust plume may go into:

- frozen flow losses, reducing efficiency
- recombination heating, raising thrust and efficiency

Kinetic modeling will determine which of these happen.

Anode Sheath and Erosion

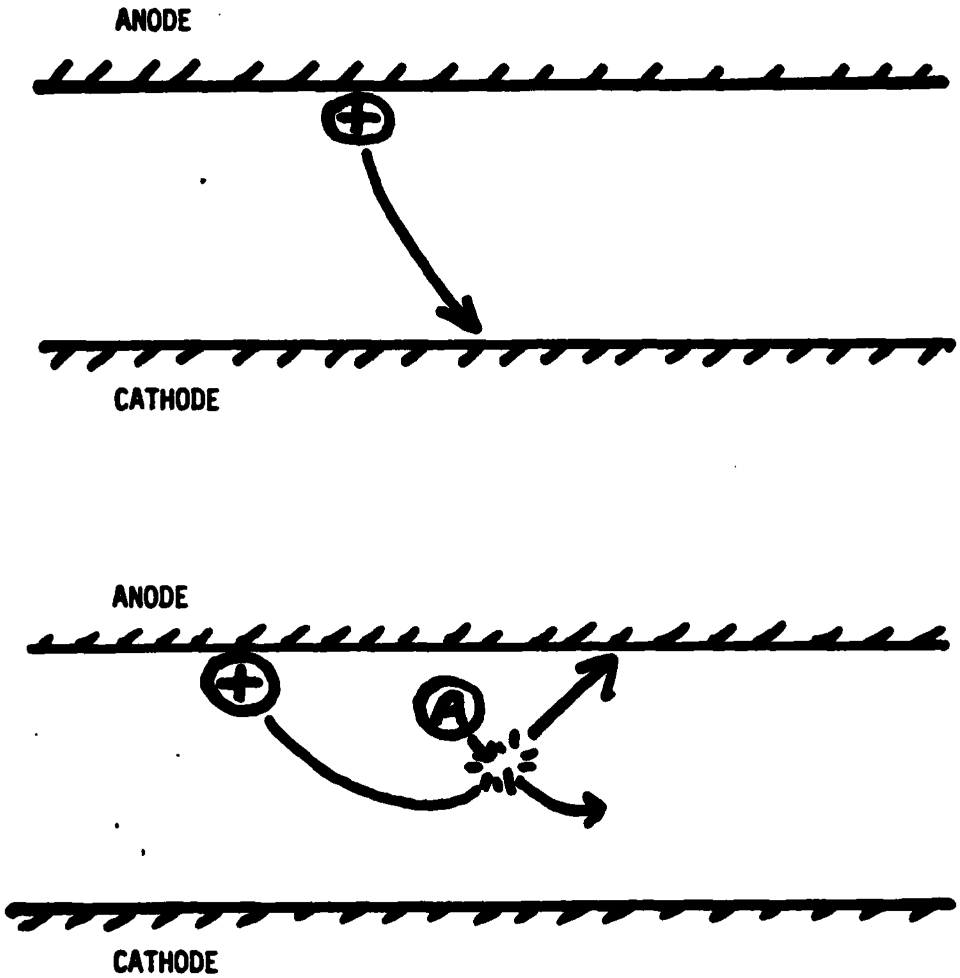

FIG. 8: Possible ion trajectories for the Kuriki-Onishi erosion mechanism are shown

Kuriki and Onishi postulate that ions created in the high voltage part of the anode sheath could travel, strike an electrode, and sputter it. Normally the ion would strike the cathode. It could however undergo a charge exchange collision and strike the anode. Important questions are:

- Under what conditions are such ions created and how many are created?
- Can this mechanism be avoided by not operating so near onset or injecting mass near the anode?

Boundary Layer and Erosion:

Technical Approach

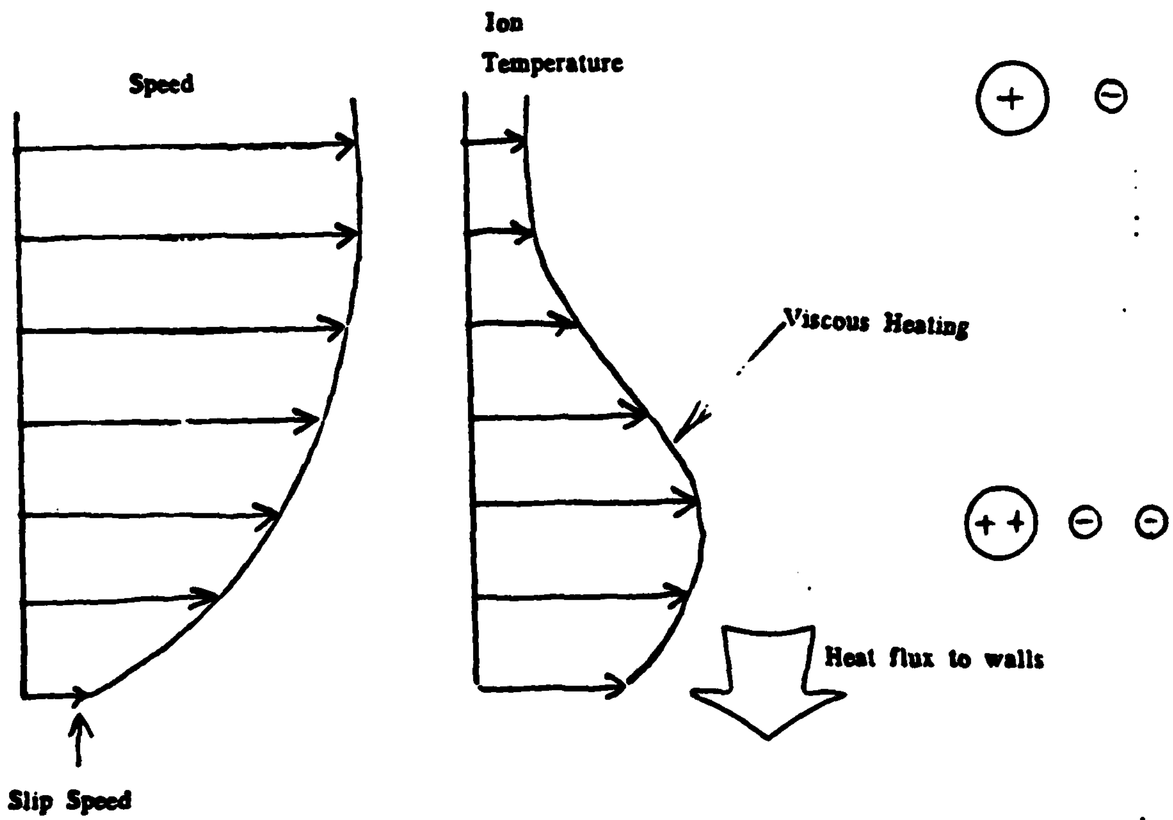

FIG. 9: *The affect of viscous and thermal boundary layers on wall conditions in MPD thrusters is shown*

The supersonic, two-temperature, non-equilibrium viscous and thermal boundary layer in MPD thrusters has not yet been analyzed.

- **It is strongly ionized, unlike MHD energy converter boundary layers.**
- **It carries current and suffers ohmic heating, unlike plasma boundary layers in reentry problems.**

Boundary Layer and Erosion:

Expected Results

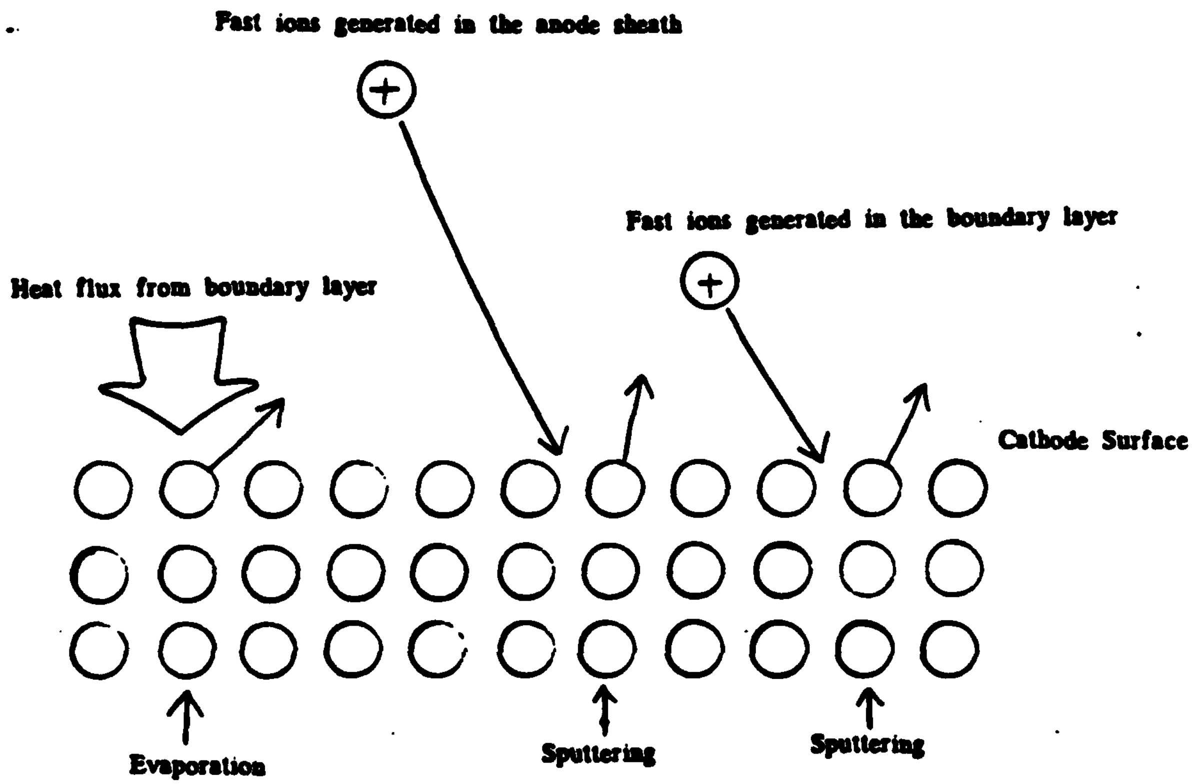

FIG. 10: Some erosion mechanisms associated with the boundary layer are shown.

Boundary layer analysis will help resolve the importance of the competing mechanisms of erosion:

- Evaporation, caused by heat transfer with hot atoms and ions in boundary layer
- Sputtering, caused by fast ions generated thermally in the boundary layer
- Sputtering, caused by fast ions generated in the anode sheath

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